

WHAT IS CLAIMED IS:

1 1. An optical frequency shifter capable of performing all-optical
2 frequency translation comprising:
3 a first stage including a first nonlinear optical material having a first effective
4 nonlinearity; and
5 a second stage including a second nonlinear optical material having a second
6 effective nonlinearity;
7 said first effective nonlinearity having a first spatial distribution in said first
8 nonlinear optical material such that a first nonlinear optical interaction is achieved between a
9 first pump channel having a first pump frequency, a signal channel having a signal frequency,
10 and an intermediate channel having an intermediate frequency;
11 said second effective nonlinearity having a second spatial distribution in said
12 second nonlinear optical material such that a second nonlinear optical interaction is achieved
13 between a second pump channel having a second pump frequency, said intermediate channel
14 and a converted channel having a converted frequency;
15 such that a shift frequency differentiates said signal frequency from said
16 converted frequency.

1 2. The optical frequency shifter of claim 1, further comprising one or
2 more couplers for coupling at least a portion of said signal channel, said first pump channel,
3 said intermediate channel, said second pump channel and said converted channel between
4 said first stage and said second stage.

1 3. The optical frequency shifter of claim 1, further comprising one or
2 more couplers for coupling at least a portion of said signal channel, said first pump channel,
3 said intermediate channel, said second pump channel and said converted channel into and out
4 of said first stage and said second stage.

1 4. The optical frequency shifter of claim 1, wherein at least a portion of
2 each of said first spatial distribution and said second spatial distribution includes one or more
3 quasi-phase-matching gratings.

1 5. The optical frequency shifter of claim 1, wherein at least a portion of
2 said first nonlinear optical interaction and said second nonlinear optical interaction are second
3 order nonlinear optical interactions.

1 6. The optical frequency shifter of claim 1, wherein at least a portion of
2 said first nonlinear optical interaction and said second nonlinear optical interaction are quasi-
3 phase-matched nonlinear optical interactions.

1 7. An optical frequency shifter, comprising:
2 a first nonlinear optical material having a first quasi-phase-matching structure;
3 and
4 a second nonlinear optical material having a second quasi-phase-matching
5 structure;
6 said first quasi-phase-matching structure configured such that a first quasi-
7 phase-matched interaction is achieved between a first pump channel having a first pump
8 frequency, a signal channel having a signal frequency, and an intermediate channel having an
9 intermediate frequency;
10 said second quasi-phase-matching structure configured such that a second
11 quasi-phase-matched interaction is achieved between a second pump channel having a second
12 pump frequency, said intermediate channel, and a converted channel having a converted
13 frequency;
14 such that a shift frequency differentiates said converted frequency from said
15 signal frequency.

1 8. The optical frequency shifter of claim 7 wherein said frequency
2 shifting is performed simultaneously on a plurality of signal channels having a plurality of
3 signal frequencies thereby generating a plurality of intermediate channels having a plurality
4 of intermediate frequencies and a plurality of converted channels having a plurality of
5 converted frequencies.

1 9. The optical frequency shifter of claim 7 wherein said shift frequency is
2 independent of said signal frequency.

1 10. The optical frequency shifter of claim 7 wherein said shift frequency is
2 independent of said plurality of signal frequencies.

1 11. The optical frequency shifter of claim 7 wherein said first and second
2 quasi-phase-matching structures are configured such that said shift frequency is a function of
3 said first pump frequency and said second pump frequency.

1 12. The optical frequency shifter of claim 7 wherein said first and second
2 quasi-phase-matching structures are configured such that said shift frequency is defined as
3 the difference between said first pump frequency and said second pump frequency.

1 13. The optical frequency shifter of claim 7, wherein said first and second
2 quasi-phase-matching structures are configured such that said shift frequency is defined as
3 twice the difference between said first pump frequency and said second pump frequency.

1 14. The optical frequency shifter of claim 7, further comprising an optical
2 filter for discriminating between said signal channel and said converted channel.

1 15. The optical frequency shifter of claim 8, further comprising an optical
2 filter for discriminating between said plurality of signal channels and said plurality of
3 converted channels.

1 16. The optical frequency shifter of claim 7, wherein said first quasi-
2 phase-matching structure and said second quasi-phase-matching structure each include one or
3 more of difference frequency mixers, sum frequency mixers, optical parametric amplifiers,
4 optical parametric generators and second harmonic generators.

1 17. The optical frequency shifter of claim 7, wherein said first quasi-
2 phase-matched interaction includes cascaded second harmonic generation and difference
3 frequency generation.

1 18. The optical frequency shifter of claim 7, wherein said second quasi-
2 phase-matched interaction includes cascaded second harmonic generation and difference
3 frequency generation.

1 19. The optical frequency shifter of claim 7 wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 a Fourier synthetic grating.

1 20. The optical frequency shifter of claim 7, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 a chirped grating.

1 21. The optical frequency shifter of claim 7, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 an apodized grating.

1 22. The optical frequency shifter of claim 7, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 one or more waveguides.

1 23. The optical frequency shifter of claim 7, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure utilize
3 one or more waveguides for guiding one or more of said first pump channel, said second
4 pump channel, said signal channel, said intermediate channel, and said converted channel.

1 24. The optical frequency shifter of claim 8 wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure utilize
3 one or more waveguides for guiding one or more of said first pump channel, said second
4 pump channel, said plurality of signal channels, a plurality of intermediate channels, and said
5 plurality of converted channels.

1 25. The optical frequency shifter of claim 22, wherein each waveguide
2 includes one or more of zinc in-diffused, titanium in-diffused, proton exchanged, annealed
3 proton exchanged, buried and surface waveguides.

1 26. The optical frequency shifter of claim 22, wherein each waveguide
2 includes one or more of couplers, directional couplers, junctions, mode filters, tapers,
3 segmentations, and bends.

1 27. The optical frequency shifter of claim 7 further comprising
2 polarization insensitive apparatus to enable the conversion of signal channels having a
3 plurality of states of electromagnetic polarization.

1 28. The optical frequency shifter of claim 7, further comprising a coupler
2 for coupling said intermediate channel into said second quasi-phase-matching structure.

1 29. The optical frequency shifter of claim 7, further comprising an
2 intermediate channel coupler for coupling said intermediate channel from said first quasi-
3 phase-matching structure into said second quasi-phase-matching structure.

1 30. The optical frequency shifter of claim 7, further comprising a first
2 pump source for providing said first pump channel.

1 31. The optical frequency shifter of claim 7, further comprising a second
2 pump source for providing said second pump channel.

1 32. The optical frequency shifter of claim 7, further comprising a signal
2 source for providing said signal pump channel.

1 33. The optical frequency shifter of claim 7, further comprising one or
2 more acousto-optic frequency shifters for performing at least a portion of said frequency
3 shifting.

1 34. The optical frequency shifter of claim 7, further comprising one or
2 more electro-optic frequency shifters for performing at least a portion of said frequency
3 shifting.

1 35. An optical frequency shifter, comprising:
2 a monolithic nonlinear optical material having a first quasi-phase-matching
3 structure and a second quasi-phase-matching structure;
4 said first quasi-phase-matching structure configured such that a first quasi-
5 phase-matched interaction is achieved between a first pump channel having a first pump
6 frequency, a signal channel having a signal frequency, and an intermediate channel having an
7 intermediate frequency;
8 said second quasi-phase-matching structure configured such that a second
9 quasi-phase-matched interaction is achieved between a second pump channel having a second
10 pump frequency, said intermediate channel, and a converted channel having a converted
11 frequency;
12 such that a shift frequency differentiates said converted frequency from said
13 signal frequency.

1 36. The optical frequency shifter of claim 35, wherein said frequency
2 shifting is performed simultaneously on a plurality of signal channels having a plurality of
3 signal frequencies thereby generating a plurality of intermediate channels having a plurality
4 of intermediate frequencies and a plurality of converted channels having a plurality of
5 converted frequencies.

1 37. The optical frequency shifter of claim 35, wherein said shift frequency
2 is independent of said signal frequency.

1 38. The optical frequency shifter of claim 36 wherein said shift frequency
2 is independent of said plurality of signal frequencies.

1 39. The optical frequency shifter of claim 35, wherein said first and second
2 quasi-phase-matching structures are configured such that said shift frequency is a function of
3 said first pump frequency and said second pump frequency.

1 40. The optical frequency shifter of claim 35, wherein said first and second
2 quasi-phase-matching structures are configured such that said shift frequency is defined as
3 the difference between said first pump frequency and said second pump frequency.

1 41. The optical frequency shifter of claim 35, wherein said first and second
2 quasi-phase-matching structures are configured such that said shift frequency is defined as
3 twice the difference between said first pump frequency and said second pump frequency.

1 42. The optical frequency shifter of claim 35, further comprising an optical
2 filter for discriminating between said signal channel and said converted channel.

1 43. The optical frequency shifter of claim 36 further comprising an optical
2 filter for discriminating between said plurality of signal channels and said plurality of
3 converted channels.

1 44. The optical frequency shifter of claim 35, wherein said first quasi-
2 phase-matching structure and said second quasi-phase-matching structure each include one or
3 more of difference frequency mixers, sum frequency mixers, optical parametric amplifiers,
4 optical parametric generators and second harmonic generators.

1 45. The optical frequency shifter of claim 35, wherein said first quasi-
2 phase-matched interaction includes cascaded second harmonic generation and difference
3 frequency generation.

1 46. The optical frequency shifter of claim 35, wherein said second quasi-
2 phase-matched interaction includes cascaded second harmonic generation and difference
3 frequency generation.

1 47. The optical frequency shifter of claim 35, wherein one both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 a Fourier synthetic grating.

1 48. The optical frequency shifter of claim 35, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 a chirped grating.

1 49. The optical frequency shifter of claim 35, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 an apodized grating.

1 50. The optical frequency shifter of claim 35, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure include
3 one or more waveguides.

1 51. The optical frequency shifter of claim 35, wherein one or both of said
2 first quasi-phase-matching structure and said second quasi-phase-matching structure utilize
3 one or more waveguides for guiding one or more of said first pump channel, said second
4 pump channel, said signal channel, said intermediate channel, and said converted channel.

1 52. The optical frequency shifter of claim 36 wherein one or more of said
2 first quasi-phase-matching structure and second said quasi-phase-matching structure utilize
3 one or more waveguides for guiding one or more of said first pump channel, said second
4 pump channel, said plurality of signal channels, a plurality of intermediate channels, and said
5 plurality of converted channels.

1 53. The optical frequency shifter of claim 50, wherein each waveguide
2 includes one or more of zinc in-diffused, titanium in-diffused, proton exchanged, annealed
3 proton exchanged, buried and surface waveguides.

1 54. The optical frequency shifter of claim 50, wherein each waveguide
2 includes one or more of couplers, directional couplers, junctions, mode filters, tapers,
3 segmentations, and bends.

1 55. The optical frequency shifter of claim 35, further comprising
2 polarization insensitive apparatus to enable the conversion of signal channels having a
3 plurality of states of electromagnetic polarization..

1 56. The optical frequency shifter of claim 35, further comprising an
2 intermediate channel coupler for coupling said intermediate channel from said first quasi-
3 phase-matching structure into said second quasi-phase-matching structure.

1 57. The optical frequency shifter of claim 35, further comprising a first
2 pump source for providing said first pump channel.

1 58. The optical frequency shifter of claim 35, further comprising a second
2 pump source for providing said second pump channel.

1 59. The optical frequency shifter of claim 35, further comprising a signal
2 source for providing said signal pump channel.

1 60. The optical frequency shifter of claim 35, further comprising one or
2 more acousto-optic frequency shifters for performing at least a portion of said frequency
3 shifting.

1 61. The optical frequency shifter of claim 35, further comprising one or
2 more electro-optic frequency shifters for performing at least a portion of said frequency
3 shifting.

1 62. An optical frequency shifter, comprising:
2 a first converter stage capable of performing a first frequency shift; and
3 a second converter stage capable of performing a second frequency shift;

4 said first converter stage including a first quasi-phase-matching structure in a
5 first nonlinear optical material, and a second quasi-phase-matching structure in a second
6 nonlinear optical material;

7 said first quasi-phase-matching structure configured such that a first quasi-
8 phase-matched interaction is achieved between a first pump channel having a first pump
9 frequency, a first signal channel having a first signal frequency, and a first intermediate
10 channel having a first intermediate frequency;

11 said second quasi-phase-matching structure configured such that a second
12 quasi-phase-matched interaction is achieved between a second pump channel having a second
13 pump frequency, said first intermediate channel, and a first converted channel having a first
14 converted frequency;

15 said second converter stage including a third quasi-phase-matching structure
16 in a third nonlinear optical material, and a fourth quasi-phase-matching structure in a fourth
17 nonlinear optical material;

18 said third quasi-phase-matching structure configured such that a third quasi-
19 phase-matched interaction is achieved between a third pump channel having a third pump
20 frequency, a second signal channel having a second signal frequency, and a second
21 intermediate channel having a second intermediate frequency;

22 said fourth quasi-phase-matching structure configured such that a fourth quasi-
23 phase-matched interaction is achieved between a fourth pump channel having a fourth pump
24 frequency, said second intermediate channel, and a second converted channel having a
25 second converted frequency.

1 63. An optical frequency shifter, comprising:

2 a first converter capable of receiving a first signal channel having a first signal
3 frequency and generating a first converted channel having a first converted frequency,
4 wherein a first frequency shift differentiates said first converted frequency from said first
5 signal frequency;

6 a second converter capable of receiving a second signal channel having a
7 second signal frequency and generating a second converted channel having a second
8 converted frequency, wherein a second frequency shift differentiates said second converted
9 frequency from said second signal frequency; and

10 a coupling structure for coupling at least a portion of said first signal channel,
11 said second signal channel, said first converted channel and said second converted channel,
12 between said first converter and said second converter.

1 64. The optical frequency shifter of claim 63 further comprising a plurality
2 of said converters.

1 65. The optical frequency shifter of claim 63, wherein said first signal
2 channel comprises a plurality of first signal channels having a plurality of first signal channel
3 frequencies, and wherein said first converted channel comprises a plurality of first converted
4 channels having a plurality of first converted channel frequencies.

1 66. The optical frequency shifter of claim 63, wherein said second signal
2 channel comprises a plurality of second signal channels having a plurality of second signal
3 channel frequencies, and wherein said second converted channel comprises a plurality of
4 second converted channels having a plurality of second converted channel frequencies.

1 67. The optical frequency shifter of claim 63, wherein said first converter
2 stage further includes:

3 a first quasi-phase-matching structure in a first nonlinear optical material, and
4 a second quasi-phase-matching structure in a second nonlinear optical material;

5 said first quasi-phase-matching structure configured such that a first quasi-
6 phase-matched interaction is achieved between a first pump channel having a first pump
7 frequency, said first signal channel, and a first intermediate channel having a first
8 intermediate frequency;

9 said second quasi-phase-matching structure configured such that a second
10 quasi-phase-matched interaction is achieved between a second pump channel having a second
11 pump frequency, said first intermediate channel, and said first converted channel.

1 68. The optical frequency shifter of claim 63, wherein said second
2 converter stage further includes:

3 a third quasi-phase-matching structure in a third nonlinear optical material,
4 and a fourth quasi-phase-matching structure in a fourth nonlinear optical material;

5 said third quasi-phase-matching structure configured such that a third quasi-
6 phase-matched interaction is achieved between a third pump channel having a third pump

7 frequency, said second signal channel, and a second intermediate channel having a second
8 intermediate frequency;
9 said fourth quasi-phase-matching structure configured such that a fourth quasi-
10 phase-matched interaction is achieved between a fourth pump channel having a fourth pump
11 frequency, said second intermediate channel, and said second converted channel.

1 69. The optical frequency shifter of claim 63, wherein said first converter
2 stage further includes an acousto-optic frequency shifter.

1 70. The optical frequency shifter of claim 63, wherein said second
2 converter stage further includes an acousto-optic frequency shifter.

1 71. The optical frequency shifter of claim 63, wherein said first converter
2 stage further includes an electro-optic frequency shifter.

1 72. The optical frequency shifter of claim 63, wherein said second
2 converter stage further comprises an electro-optic frequency shifter.

1 73. An optical frequency shifter, capable of performing optical frequency
2 shifting, comprising a nonlinear optical material having an effective nonlinearity d_{eff} , and a
3 quasi-phase-matching structure in said nonlinear optical material, such that a first channel
4 and a second channel both quasi-phase-match for performing optical frequency mixing.

1 74. The optical frequency shifter of claim 73 wherein said optical
2 frequency shifter includes a first difference frequency mixing stage quasi-phase-matched for
3 a first pump channel, and a second difference frequency mixing stage quasi-phase-matched
4 for a second pump channel.

1 75. An optical frequency shifter, capable of performing frequency shifting
2 on one or more signal channels, comprising a nonlinear optical material having an effective
3 nonlinearity d_{eff} , whereby said effective d_{eff} is spatially distributed in said nonlinear optical
4 material so as to form a quasi-phase-matching structure, wherein two pump channels quasi-
5 phase-match for performing frequency shifting, wherein a resulting frequency translation is a
6 function of the difference in frequencies between said pump channels.

1 76. An optical frequency shifter comprising:

2 a plurality of N optical frequency translation stages, with each optical
3 frequency translation stage indexed by an integer n, $n = 0, \dots N$, and with each optical
4 frequency translation stage having an input port, and an output port, with the optical
5 frequency translation stage for receiving an input signal at the input port and for translating a
6 received input signal into a translated output signal provided by the output port, with the
7 translated output signal having a frequency equal to an input signal frequency translated by a
8 frequency equal to $2n \Delta$, where Δ is a frequency shift having a selected value; and
9 an input signal coupling structure for coupling the input port of an nth optical
10 frequency translation stage to the output ports of all optical frequency translation stages
11 preceding the nth optical stage.

1 77. The optical frequency shifter of claim 76 wherein each optical
2 frequency translation stage comprises:

3 a first stage that receives a first pump signal, generates a second harmonic of
4 the first pump signal, and mixes the second harmonic of the first pump signal with the input
5 signal to generate a first stage output signal; and

6 a second stage that receives a second pump signal, generates a second
7 harmonic of the second pump signal, and mixes the second harmonic of the second pump
8 signal with the first stage output signal to generate an OFS stage output signal.

1 78. The optical frequency shifter of claim 76 wherein each optical
2 frequency translation stage comprises:

3 a first stage that receives a first pump signal, and mixes the first pump signal
4 with the input signal to generate a first stage output signal; and

5 a second stage that receives a second pump signal, and mixes the second pump
6 signal with the first stage output signal to generate an OFS stage output signal.

1 79. The optical frequency shifter of claim 76 where said input signal
2 coupling structure comprises:

3 a set of n-1 beamsplitters disposed to split the output beams of n-1 preceding
4 translation stages and provide a portion of the n-1 output beams the input port of the nth
5 translation stage.

1 80. A method for synthesizing a plurality of optical frequencies
2 comprising the steps of:

3 receiving an input signal having an input signal frequency;
 4 performing a first translation of a frequency shift of Δ on the input signal to
 5 generate a first translated signal having a frequency translated from the input signal
 6 frequency by Δ ;
 7 performing a second translation of a frequency shift of 2Δ on both the input
 8 signal and the first translated signal to generate second and third translated signals translated
 9 from the input signal frequency by 2Δ and 3Δ ; and
 10 sequentially performing n subsequent translations, n being an integer equal to
 11 $3, \dots, N$, with the n th translation translating the frequency of the input signal and all
 12 previously generated translated signals by a frequency shift of $2^n\Delta$ to generate 2^n translated
 13 signals translated from the input signal frequency by $n\Delta, n+1\Delta, n+2\Delta, \dots, 2^n - 2\Delta, 2^n - 1\Delta$.

1 81. The method of claim 80 where said step of performing a translation
 2 comprises the steps of:
 3 receiving first and second pump signals at first and second pump frequencies
 4 and at least one input signal, with the first and second pump frequencies having frequency
 5 values near a frequency value of the input signal;
 6 generating second harmonics of the first and second pump signals to form first
 7 and second doubled pump signals having doubled first and second pump frequencies; and
 8 mixing the input signal with the first doubled pump signal to form a first
 9 mixed signal and mixing the first mixed signal with the second doubled pump signal to
 10 generate an output signal shifted in frequency from the input signal by double the difference
 11 of the doubled first and second pump frequencies.

1 82. The method of claim 81 further comprising the steps of:
 2 providing a first pump signal having the first pump frequency equal to a basic
 3 pump frequency; and
 4 providing a second pump signal having a second pump frequency substantially
 5 equal to the sum of the base pump frequency and $(1/2)\Delta$ multiplied by 2 raised to the power
 6 of $(n - 1)$.

1 83. The method of claim 80 where said step of performing a translation
 2 comprises the steps of:

3 receiving first and second pump signals at first and second pump frequencies
4 and at least one input signal, with the first and second pump frequencies having frequency
5 values near about double the frequency value of the input signal; and
6 mixing the input signal with the first pump signal to form a first mixed signal
7 and mixing the first mixed signal with the second pump signal to generate an output signal
8 shifted in frequency from the input signal by the difference of the first and second pump
9 frequencies.

1 84. An optical frequency shifter comprising:
2 a plurality of optical frequency translation stages, each stage for translating the
3 frequency of an input signal by a frequency shift, with the frequency shift of a following
4 stage equal about double the frequency shift of a preceding stage; and
5 an input signal coupling structure for coupling the input port of each optical
6 frequency translation stage to the output ports of all optical frequency translation stages
7 preceding the optical stage.